

# Ca II and DLA ABSORPTION LINE SYSTEMS: DUST, METALS AND STAR FORMATION AT $0.4 < z < 1.3$

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Absorption line studies of galaxies along the line-of-sight to distant quasars allow a direct observational link between the properties of the extended gaseous disk/halo and of the star forming region of galaxies. In these proceedings we review recent work on Ca II absorbers detected in the SDSS at  $0.4 < z < 1.3$  which, because of their dust content and chemical properties, may lie spatially closer to the central host galaxy than most DLAs. We present direct evidence for the presence of star formation, through observation of the [O II]  $\lambda\lambda 3727, 3730$  emission line, in both Ca II absorbers and Mg II-selected Damped-Lyman- $\alpha$  (DLA) systems. The measured SFR from light falling within the SDSS fibre apertures (corresponding to physical radii of  $6 - 9 h^{-1}$  kpc) is  $0.11 - 0.48 M_{\odot} \text{yr}^{-1}$  for the Ca II-absorbers and  $0.11 - 0.14 M_{\odot} \text{yr}^{-1}$  for the Mg II-selected DLAs. The contribution of both Ca II absorbers and DLAs to the total observed star formation rate density,  $\dot{\rho}^*$ , in the redshift range  $0.4 < z < 1.3$ , is small,  $< 10\%$ . Our result contrasts with recent conclusions, based on the Schmidt law, that DLA absorbers can account for the majority of the total observed  $\dot{\rho}^*$  in the same redshift range.

## 1 Introduction

The strong intervening hydrogen and metal absorption lines observed in quasar spectra are generally thought to be caused by gas associated with galaxies along the line-of-sight. Damped Lyman- $\alpha$  (DLA) systems are the most extreme subset of these absorbers, defined through their high column densities,  $N(\text{H I}) > 2 \times 10^{20} \text{ cm}^{-2}$ , of neutral hydrogen gas.

In principle, galaxies detected through the absorption of background quasar light by their interstellar gas provide a unique view of the chemical evolution of galaxies and their outer gaseous halos over the majority of the age of the universe, unaffected by the luminosity bias suffered by traditional emission-selected galaxy samples. They present the opportunity to accurately probe metallicity, dust attenuation, disk dynamics to large radii and gas cross-section weighted star formation. Indeed, accurate chemical abundances of these absorbers are already being used to provide useful comparisons to SPH galaxy evolution simulations<sup>1</sup>.

However, the true nature of absorption systems is unclear: their persistently low metallicities<sup>2,3</sup> and dust contents<sup>4</sup> may suggest they exist within galaxies with a low degree of chemical evolution, or, probe only the outer, relatively metal poor, parts of disks. Follow-up deep imaging campaigns have had mixed success with regard to identification of the host galaxy responsible for the absorber. At high redshift, interest has focussed on the DLAs, where only a handful of suitable candidates have been detected<sup>5</sup>, generally through Lyman- $\alpha$  emission. At lower redshift far fewer DLAs are known, as the Lyman- $\alpha$  line moves into the ultraviolet, only accessible to (the now inactive) STIS on the Hubble Space Telescope. The few host galaxies identified appear to be morphologically diverse and span a wide range of luminosities<sup>6</sup>. A residual concern is the impact of dust obscuration bias: it is possible that the most metal rich, and therefore dustiest, absorbers are being missed from magnitude-limited quasar surveys, although DLAs with such extreme properties have proved elusive so far<sup>7</sup> (see also contribution by C. Peroux in these proceedings). The large gap in our understanding that remains between the absorption- and emission-selected galaxy populations severely restricts our ability to gain a more complete understanding of galaxy evolution.

### 1.1 *Ca II absorbers*

Recently, a different class of absorption line system has received renewed attention, the Ca II absorbers<sup>8</sup>. Although extremely rare (number density about 30% that of DLAs), a large sample with  $0.4 < z_{\text{abs}} < 1.3$  has now been identified in the Sloan Digital Sky Survey (SDSS) DR4 spectroscopic database. In the local interstellar medium (ISM) calcium is severely depleted onto dust grains, and Ca II is a minor ionisation state with an ionisation potential below that of hydrogen. Significant columns of Ca II are therefore expected to trace either, i) very high column density DLAs, ii) high *volume* density regions where a degree of self shielding can take place, or, iii) shocked gas in which dust grain destruction temporarily releases relatively large quantities of calcium into the gas phase. In these proceedings we review the unusual properties of the absorbers and present new measurements of their star formation rate (SFR), from detection of [O II]  $\lambda\lambda 3727, 3730$  in stacked SDSS spectra. We conclude by discussing some implications of our results for calculating the star formation rate in Ca II and DLA absorbers and their contribution to the total volume averaged SFR density,  $\dot{\rho}^*$ , of the universe at  $z \sim 1$ .

## 2 Reddening by Dust

Dust has three observable effects in galaxies: it selectively depletes metals in the ISM, reddens their spectral energy distributions, and causes an overall extinction of the light. Estimates of reddening from differences in the average spectral energy distributions (SEDs) of background quasars must rely on statistical studies, due to the intrinsic range in the SEDs of quasar spectra. Due, in part, to the difficulty in defining suitable samples, there are relatively few reports of evidence for dust in DLAs via the reddening effect on background quasar spectra. However, the large sample of quasars in the SDSS at similar redshifts to those containing absorption line systems allows a good estimate of the average quasar spectrum, and scatter, to be obtained. Any reddening signal in the spectra of quasars with an intervening absorber can then be found by comparing their SEDs with that of the average quasar SED at the appropriate redshift.

Figure 1 presents the reddening curves resulting from combining, in the absorber rest frame, 37 Ca II absorbers with  $0.8 < z_{\text{abs}} < 1.3$ , after each contributing spectrum has been divided by a suitable high signal-to-noise ratio (SNR) ‘average’ quasar composite spectrum. The resulting composite is fitted with extinction curves appropriate to dust in the Milky Way and the Magellanic Clouds (as indicated) to deduce the values of the colour excess,  $E(B-V)$ . The nominally better fit of the LMC dust curve to the high equivalent width (EW) Ca II sample

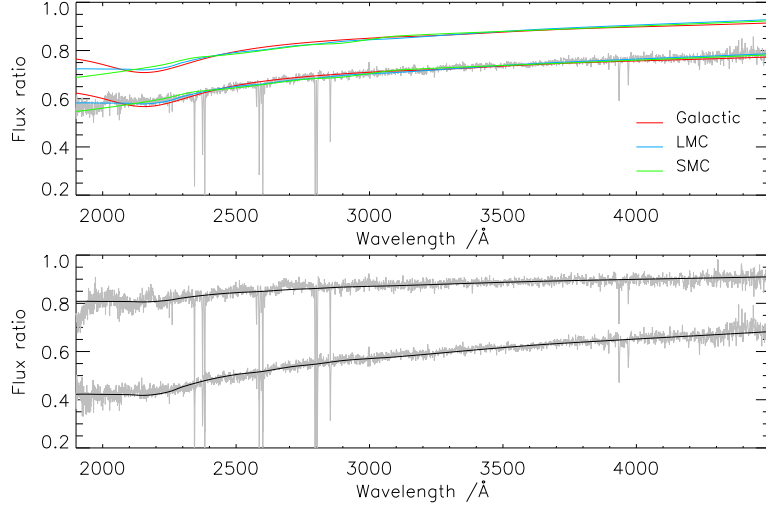


Figure 1: *Top*: Composite spectrum of the 37 quasars with Ca II absorbers, after division by an ‘average’ quasar SED. Overplotted are best-fit extinction curves with  $E(B-V) = 0.057, 0.065, 0.066$  for the MW, LMC and SMC respectively. *Bottom*: Same as for the upper panel, but with the Ca II sample now split into the ‘High-’ and ‘Low-EW’ subsamples ( $0.3 < W_{\lambda 3935} < 0.68 \text{ \AA}$  and  $W_{\lambda 3935} > 0.68 \text{ \AA}$ ). The former shows the higher extinction with  $E(B-V) = 0.103$ . Data taken from Wild, Hewett & Pettini (2006a)<sup>9</sup>.

( $W_{\lambda 3935} > 0.68 \text{ \AA}$ ) suggests the presence of a weak  $2175 \text{ \AA}$  dust feature, although, with the currently limited statistics, this result is only tentative.

### 3 Element Depletions

A further diagnostic of the presence of dust in DLAs and metal absorption line systems comes from relative abundances of elements, such as Cr to Zn, which are depleted by differing amounts onto dust grains. Previous results have indicated that dust depletion is far less severe than in the Galactic ISM today which has further strengthened the argument that DLAs are relatively dust free compared with modern galaxies<sup>10</sup>.

While very weak metal transition lines cannot be seen in individual SDSS absorption spectra, by combining all the Ca II absorption spectra into a single composite, a high enough SNR can be reached to obtain reliable average measurements. These average values can be interpreted readily providing that: (a) the gas in the Ca II absorbers is predominantly neutral, as is the case in DLAs, and (b) the distribution of equivalent widths of the lines among the individual systems is reasonably uniform, as suggested by inspection of the individual spectra.

Figure 2 shows ion column densities relative to Zn II<sup>a</sup> measured in a composite of 27 Ca II absorbers with  $0.84 < z_{\text{abs}} < 1.3$ , compared to results from the ISM of the MW and DLAs. Zn II is used for normalisation as it is expected to suffer minimal depletion onto dust grains. The depletion pattern of the Ca II absorbers is similar to that seen in DLAs, but the overall level of depletion of the high-EW sample is higher, approaching values typical of the warm neutral medium of the Milky Way<sup>12</sup>.

### 4 Star formation from [O II] $\lambda\lambda 3727, 3730$ emission

A complete picture relating the gas cross-section, ionisation state and chemical abundances of the ISM of galaxies to their stellar and nebular emission properties requires knowledge of

<sup>a</sup>These are quoted in the standard way, relative to solar abundances<sup>11</sup>:  $[X/Zn] \equiv \log [N(X)/N(Zn)] - \log [X/Zn]_{\odot}$ .

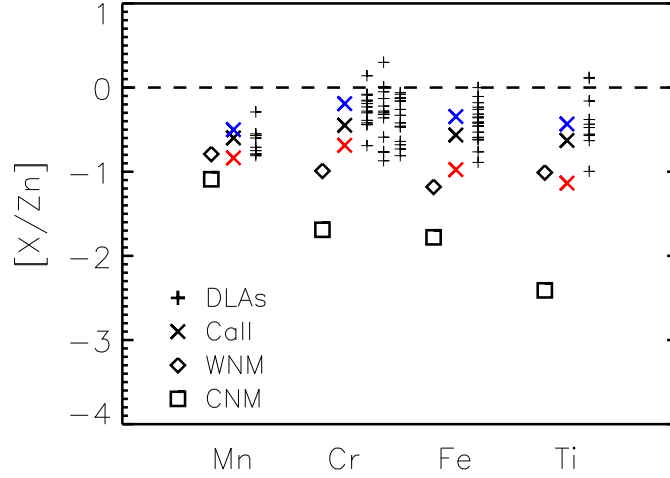


Figure 2: The abundances of refractory elements relative to Zn II in the warm and neutral ISM of the Milky Way<sup>12</sup> and DLAs compared to the Ca II absorbers. The upper, middle, and lower Ca II points are for the low-EW, combined, and high-EW samples respectively of Wild, Hewett & Pettini (2006a)<sup>9</sup>, to which the reader is referred for the sources of the DLA measurements.

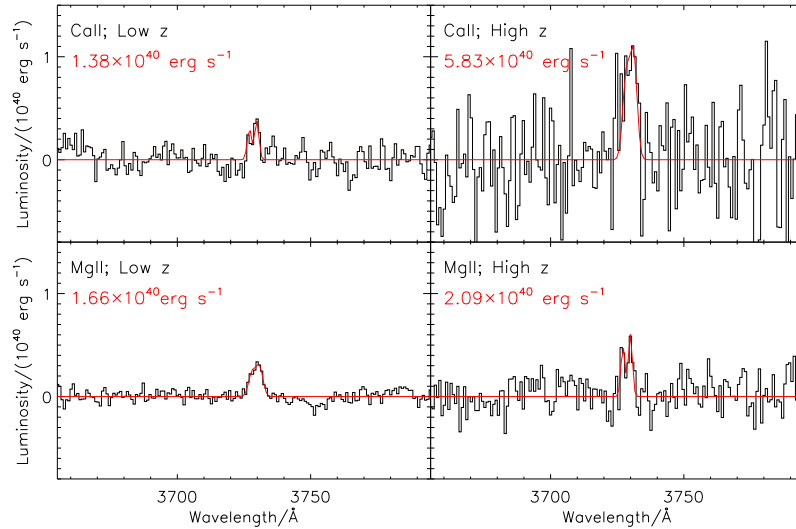


Figure 3: SDSS composite spectra of Ca II absorption line systems (top) and Mg II-selected DLA candidates (bottom) showing the region of [O II]  $\lambda\lambda 3727, 3730$  in redshift bins of  $0.4 \leq z_{\text{abs}} < 0.8$  (left) and  $0.8 \leq z_{\text{abs}} < 1.3$  (right). Flux from each contributing spectrum has been converted into luminosity before combining. Overplotted (in red lines) are two-component Gaussian fits to the emission lines. Measured line luminosities from these line fits are given in each plot. Data taken from Wild, Hewett & Pettini (2006b)<sup>13</sup>.

the SFRs of absorption-selected galaxies. However, despite considerable effort, deep follow-up imaging and spectroscopy have so far led to the identification of only small numbers of host galaxies of DLAs.

A significant breakthrough in this field is the recent detection of [O II]  $\lambda\lambda 3727, 3730$  nebular emission associated with Ca II- and Mg II-selected DLAs in stacked spectra of SDSS QSOs<sup>13</sup>. The  $1\sigma$  noise in the SDSS quasar spectra is  $\sim 1 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$  per pixel ( $\Delta v = 69 \text{ km s}^{-1}$ ), and detection limits for (close to) unresolved features in several hundred or more stacked spectra can easily reach an impressive  $10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1}$ . In Figure 3 we have reproduced the co-added SDSS spectra in the wavelength region of the [O II] doublet for 345 Ca II and 3461 strong Mg II absorption line galaxies with  $0.4 < z_{\text{abs}} < 1.3$  showing clear detection of the nebular emission lines from H II regions associated with the absorbers. Each spectrum was converted into units of luminosity before combining, and the best two-component Gaussian fits are overplotted. Composite spectra are shown for low ( $\langle z \rangle \simeq 0.6$ ) and high ( $\langle z \rangle \simeq 1.0$ ) redshift sub-samples.

The emission line detections allow for the first time a direct estimate of the average SFR in an absorption-selected galaxy population. Using the conversion between [O II] line luminosity and SFR proposed by Kewley et al.<sup>14</sup> results in values of 0.11 (0.48)  $\text{M}_{\odot} \text{ yr}^{-1}$  for the low- (high-) redshift Ca II samples (after correcting for dust attenuation) and 0.11 (0.14)  $\text{M}_{\odot} \text{ yr}^{-1}$  for the DLAs selected by strong Mg II absorption.

These values apply to the observed SFR within the finite aperture of the SDSS fibre, which is centered on the quasar and not on the absorber host galaxy. The proper transverse radius covered by a 3 arcsec fibre is  $\sim 7.5 h^{-1} \text{ kpc}$  at  $z = 0.6$  and  $\sim 8.4 h^{-1} \text{ kpc}$  at  $z = 1$ , i.e. comparable to the expected size of the star forming extent of  $L^*$  galaxies<sup>b</sup>. Thus, the fibre may be covering a fraction of empty sky, which has implications for measures of SFR per unit area of the absorbers; or the fibre may exclude a fraction of the galaxy light, with implications for estimating the total SFR per absorber. These results allow us to place lower limits on the SFR per unit area of the absorbers; however, further interpretation requires an estimate of the physical extent of the absorbers. Both observational<sup>6</sup> and recent theoretical work predict mean impact parameters between low- to intermediate-redshift DLAs and host galaxies of order  $10 h^{-1} \text{ kpc}$ , i.e. DLAs are caused by extended gaseous halos/disks around central galaxies. Adopting this model we estimate aperture corrections and derive SFRs per unit area of  $11 (36) \times 10^{-4} h^2 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  for the Ca II absorbers and  $14 (11) \times 10^{-4} h^2 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  for Mg II-selected DLAs.

The SFRs per unit area for DLAs lie at least a factor of five below the prediction of the Schmidt law<sup>15</sup>, which relates the surface density of neutral gas and SFR in galaxies. A straightforward calculation also shows that the contribution of both the Mg II-selected DLAs and Ca II absorbers to the global SFR density of the universe at  $z \lesssim 1$  is  $< 10\%$ . Our results are dramatically different from those of Hopkins et al. (2005)<sup>16</sup>, who proposed that DLA absorbers are responsible for  $\sim 80\%$  of the global SFR density,  $\dot{\rho}^*$ , at redshifts  $z \lesssim 1$ . Hopkins et al. assumed that the Schmidt law holds for DLA absorbers and the difference with our results is entirely attributable to the much lower, directly determined, SFR per unit area of the DLAs.

Interpretation of the results for the Ca II absorbers is less certain because their mean  $N(\text{H I})$  column densities are not yet established and the results of imaging studies to determine impact parameters and luminosities of their host galaxies are awaited.

An attractive explanation for the low observed SFR per unit area in the DLAs is that the threshold H I column density required to trigger star formation is significantly higher than in the nearby galaxies where the empirical Schmidt law was calibrated. Whatever the physical explanation, it is now difficult to escape the conclusion that only a small fraction of the star formation rate seen directly in galaxy surveys at redshifts  $z \sim 1$  is associated with DLAs. Evidently, the largest contribution to the DLA cross-section is from gas which is too diffuse to

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<sup>b</sup> A flat cosmology with  $\Omega_{\Lambda} = 0.7$ ,  $\Omega_M = 0.3$ ,  $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$  is assumed throughout

support high rates of star formation and metal production, thus explaining the generally low metallicities of most DLAs.

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